

WAVES IN SPACE PLASMA DIPOLE ANTENNA SUBSYSTEM

Mark Thomson*

ABSTRACT

The Waves In Space Plasma (WISP) flight experiment requires a 50-meter-long deployable dipole antenna subsystem (DASS) to radiate radio frequencies from the STS Orbiter cargo bay. The transmissions are to excite outer ionospheric plasma between the dipole and a free-flying receiver (Spartan) for scientific purposes. This report describes the singular DASS design requirements and how the resulting design satisfies them. A jettison latch is described in some detail. The latch releases the antenna in case of any problems which might prevent the bay doors from closing for re-entry and landing of the Orbiter.

INTRODUCTION

The DASS is composed of 25-meter-long monopoles mounted back to back in the aft end of the cargo bay as shown in Figure 1. They are deployed from the 1.2-meter-long antenna element assemblies (AEAs) shown in Figure 2. The antenna elements are storable tubular extendible members (STEMs™) which are each deployed 23.6 meters from an aperture in the deployer mechanism housing. During the experiment the Orbiter executes a number of complex maneuvers with the DASS at various deployed extensions during as many as 50 deployment cycles.

A veteran of many space flights, a STEM™ mechanism is the basic component of the DASS. It is formed into a tubular configuration from a single strip of thin metal, then spread and flattened so it can be rolled onto a spool for launch. Its simplicity is appropriate for the high degree of reliability and straightness that are demanded of the DASS antenna elements.

All functions of the AEA must have redundant backup. Furthermore, for re-entry and landing it must be possible to safe the cargo bay from failure of the monopoles despite two electrical and/or mechanical faults. If there is a failure to retract and cage the STEM, the element must be jettisoned cleanly away from the Orbiter. A unique and single-fault-tolerant jettison latch is the result of this need.

The powerful jettison latch is subject to a common problem: Just at the point of release, contact stresses go up exponentially, thus yielding or fracturing the latch. Although the mechanism was designed to be tolerant of this tendency, an anomaly was observed during initial testing. The latch and results of the anomaly are highlighted in the discussion.

* Astro Aerospace Corporation, Carpinteria, CA

The WISP experiment transmitter has a peak power of 500 watts at frequencies up to 30 MHz. This range of propagation is outside that to which the Orbiter was designed and qualified. Understandably, there is significant concern about any effects the strong radiated emissions might have on electrical equipment in the AEA and the Orbiter. Mechanisms that will be at RF potential are therefore isolated from the components that are susceptible to EMI. The requirement for a reliable jettison capability and for electrical isolation have influenced the design of the AEA to the greatest extent.

REQUIREMENTS

The AEA configuration evolved from the most influential of the electrical and mechanical DASS performance requirements.

Electrical design drivers include the following:

- Dipole lengths of 5.0, 6.0, 7.0 ± 0.01 m to 50 ± 0.05 meters
- Total shunt capacitance of 20 picofarads or less at the RF interface
- Low sensitivity to EMI
- Magnetic permeability ± 0.190 of that of free space
- Antenna element DC surface resistivity of 1,000 ohms/cm² or less
- Electrical control of safety critical functions two-fault-tolerant

Mechanical design drivers include:

- Antenna element linearity:
 - ± 1 percent tip deflection due to Orbiter induced loads based on monopole length
 - ± 4 percent tip deflection due to the worst combination of:
 - As-manufactured straightness
 - Repeatability upon multiple deployments
 - Alignment errors relative to the Orbiter
 - Thermal distortions
- Safety Critical: safe the cargo bay with a tolerance to two faults
 - Single-fault-tolerant capability to jettison the element without debris in the event of buckling or a failure to retract
 - Single-fault-tolerant capability to cage the elements during launch and landing

- 5 cm/sec (2 in/sec) minimum deployment rate
- Peak random vibration spectral density of 0.14 G² Hz, 150 to 250 Hz
- 182 kg (400 lb) maximum DASS total weight

DESIGN APPROACH

Electrical Isolation

The STEM deployer and its contiguous mechanisms are at RF potential by necessity. They are thus mounted on top of a NEMA G-11 dielectric tower structure to electrically isolate them. As shown in Figure 3 and amplified by the cutaway view in Figure 4, the electromechanical components are underneath the tower. An assembly of two electronic controllers, potentiometers, seventeen switches, wiring harnesses and 4 DC motors are mounted on grounded base plate. Actuation of the deployer and the related mechanical status indicators are attained by the rotation of hollow shafts that are also of NEMA G-11.

To meet the capacitance requirement the amount of dielectric separation between the deployer housing and the grounded base was controlled. On the basis of the surface area presented between the two large assemblies it was necessary to provide an average separation of 0.2 meters (8.0 inches) to achieve an overall DASS shunt capacitance below 20 picofarads.

Mechanical Drives

Four electromechanical actuators are powered by 28 V DC brushed gear motors that protrude from the underside of the base plate. The motors drive 25 mm (1 inch) inside diameter G-11 tubes that are visible in Figure 4. Crowned-spline couplings are used at the ends of the tubes. The pivoting splines prevent thermal distortions and misalignment between the upper and lower structures from being a concern, and carry out an important function of the jettison latch.

The motors are modular in design. Three different groupings of the modules are needed to power antenna deployment, jettison, and caging functions. A tandem motor with a redundant power-off-brake drives the STEM deployer. Redundant potentiometers track the length of the deployed STEM via a gear reduction at the output spline of this actuator. Another tandem motor drives the caging shutter mechanism, but without a brake. Two single armature motors drive the redundant jettison latches. The jettison and STEM drive motors protrude from underneath the base assembly at the near (inboard) end of the AEA in Figure 4.

Retraction stores a significant amount of potential energy in the STEM and is therefore the sizing case for the motor. Motor power is based on a deployment speed of 5 cm/sec (2 in/sec) under the worst conditions. The output speed of the gear motor was set at 9 RPM so that the jettison latch and caging mechanisms could operate slowly without further gear reductions.

All switches are actuated through smaller hollow G-11 tubes. The deployed position of the STEM is indicated accurately by rollers that fall into pre-punched slots in the STEM. Rockers attached to the rollers cause the tubes to rotate, which actuates the redundant switch assemblies attached below. A number of other status indications are available by way of switches that are actuated in the same manner. Because the indicator tubes can only rotate, the switches will not be abused during vibration testing and launch. A simple flexure fitting allows the indicator shafts to rotate without angular play while behaving like a gimbal of limited range to mitigate the need for careful alignment of the deployer and base assemblies.

Design for Cost

The chosen design approach results in an increase in size and complexity compared to what is typical for a STEM unit. It was possible to keep the cost of the AEA and related engineering relatively low, however, by taking advantage of the specified 182-kg (400-lb) maximum weight limit. A finite element model of the unit was generated to yield the loads on subassemblies. The ample weight ceiling allows individual structures and mechanisms to be of sturdy proportions. Because it is not necessary to relieve weight at every opportunity, the effort required for the detail design and machining of the parts is greatly reduced. With worst-case strength margins of 400 to 1,000 percent in most cases, the detailed stress analysis of piece parts could be carried out in a somewhat abbreviated manner. The analytical scope for the fracture critical components is significantly reduced as well.

Most space flight mechanisms require some kind of adjustment or inspection before flight. Every effort was therefore made to ensure that more complex components would not be buried within the AEA. Assembly and disassembly of the unit were streamlined by making each G-11 panel in the tower individually removable. Access to every component inside the AEA is available from several directions with a minimum of effort. The indicator shafts are easily removed for access to multiple-switch assemblies which are calibrated in a separate fixture. The motors and electronic controllers can be unbolted directly from the external surface of the base assembly. The larger G-11 tubes for the actuator drives have female splines in each end and are thus easily removed.

The STEM and Guidance Mechanism

To satisfy the overall antenna element linearity requirements, the STEM material must be formed into uncommonly straight and long lengths. The resulting elements display a basic straightness of less than ± 1.0 cm (± 0.4 inch) RMS over the 23.6-m deployed length. Straightness was measured by supporting the element on floats in a water table, which closely approximates zero-g in a plane, as shown in Figure 5.

The antenna element itself is made of beryllium copper to conform to the requirement for magnetic permeability. Its thickness is 0.18 mm (0.007 inch), and it is formed into a 34-mm (1.34-inch) diameter tubular shape from 15.2-cm (6-inches) wide flat strip, as shown in Figure 6. The resulting circumferential overlap of 153

degrees places the mechanical shear center of the element in coincidence with the geometric center of the tube.

The element is plated with silver to maintain the lowest possible surface resistivity and operating temperatures. Metallic plating is the only type of conductive coating that is compatible with the deployable STEM element, and silver has a lower α/ϵ ratio than any metal that is appropriate for plating STEMs. The maximum solar thermal gradient across the STEM is about 3°C. This results in a deflection of 0.44 m (17 in) at the tip of the element.

A special guidance mechanism supports the STEM, as shown in the figure, while adding a minimum amount of friction during retraction. Shown schematically in Figure 6, the guidance mechanism keeps pointing hysteresis upon multiple deployments within ± 0.1 degree. The combined straightness, including hysteresis, became ± 2 cm (± 0.8 inch) RMS. The stiffness of support provided by the guidance rollers and edge guides is 97 percent of the ideal value, which is based on a potted element.

Thermal Control

The original plan was to coat the antenna element deployer housing with a conductive, optically benign coating such as indium tin. A white, inorganic and electrically conductive paint developed by Marshall Space Flight Center for the tethered satellite program also came to our attention. The principle investigator ultimately decided, however, that the surface conductivity must be constant along the length of the monopole. A mismatch might not result in a consistent path for DC current to flow into the plasma when it is attached to the dipole. It thus became necessary to plate the deployer housing with silver as well as the STEM.

Silver-plating the housing results in temperatures of 180°C (356°F) when re-radiation and reflectivities of the cargo bay are accounted for. This temperature is compatible with the exclusively mechanical deployer, but not with the electronic components. It is fortunate, then, that the NEMA G-11 tower also serves as an effective thermal isolator for the base assembly. The actuators and electronics have a maximum temperature of about 70°C (158°F) during long transients, which is acceptable.

Jettison Mechanism

The height of the deployer on the pallet in the cargo bay is just sufficient to ensure that a jettisoned port-side unit will clear the remote manipulator system (RMS) arm when stowed on the sill. The monopole must be jettisoned without generating debris and with a highly predictable trajectory. The track and roller ejection scheme shown in Figure 7 were therefore selected.

During launch and normal operation, the deployer is supported by a rigid four-point support system that is integral with the aluminum jettison tracks. The outboard supports, visible in Figure 4, are VespeI™ bushings that are located on crowned pins facing outboard from the base assembly. The inboard two supports are cups

centered on cones. The cones are backed by large stacks of disc springs that are compressed in series. The jettison latch preloads the springs flat to establish a precisely repeatable deployer position. When the latch is released, the kickoff springs provide a total initial impulse of 365 kg (800 lb). This accelerates the 30-kg (65-lb) deployer to 1 m/sec over the 1-cm distance that the springs act.

Mechanical interfaces with the actuators and indicators in the base assembly are separable. The STEM deployment and caging drive mechanisms have pairs of spur gears meshed at the points of separation. The teeth simply disjoin laterally along a line connecting the pitch axes. The indicator mechanisms, which normally exchange rotary motion through levers with pins in forks, disengage similarly. If any one of these interfaces become jammed, the high kickoff force ensures that the parts will separate.

Redundant negator motors then accelerate the deployer at 0.3 g up to 2.3 m/sec until only a few rollers remain engaged with the track to guide a straight trajectory away from the Orbiter. Each negator motor pulls one end of a shared cable that is wrapped around pulleys on the deployer. The course of the cable through the mechanism is well-shielded, and all features near the pulleys are controlled to defeat jamming. The cable is attached to each reel with less than 1 inch of excess length when the latch is armed. If one of the negator motors fails to operate, the other reel simply pulls in all the cable. The 23-kg (50-lb) accelerating force normally exerted by both negators on the deployer is reduced by only a few percent when one negator is operating. The losses are due to cable friction around what becomes a 2:1 purchase.

An initial concern was that the deployer might spin when jettisoned because the jettison tracks and spring forces do not act through the deployer center of gravity. A vertical, off-loaded jettison test was therefore conducted which verified the function of the latch and proved that a significant rotation is not induced by the mechanism.

Jettison Latch and Preload Assembly

The safety-critical jettison latch is shown in Figure 8. The two cups that seat the deployer on the inboard ejection cones are machined from blocks of Custom 455™ stainless steel. The cup blocks have teeth that face inward to engage the toothed faces of the latches. The teeth make contact at an angle of 30 degrees. The latches are also made of Custom 455™. They are held in engagement with the cup block by the presence of two square-headed Nitronic 60™ release shafts and a cylindrical Custom 455™ shuttle rod in between. The latches swivel inward on pivots in the jettison track assembly to release the deployer. All the latch components are dry-film lubricated with Vitrolube™ to provide durable lubrication and inhibit metal-to-metal contact.

Finally, disc springs on each pivoting latch arm is tightened against the jettison track assembly to pull the deployer cups onto the cones with a controlled preload of 1,400 kg (3,100 lb). This load is 25 percent greater than the maximum load resulting from the specified launch limit load environment per a detailed finite

element analysis. The 30-degree inclination of the latch faces cam the latches inward to squeeze the release shafts and shuttle rod with up to 700 kg (1,550 lb). If either release shaft is pulled out of engagement, the resulting gap is wide enough for both latches to swivel inwards while the shuttle rod finds a more neutral position.

Jettison Latch Release Shaft

The release shafts have acme lead screws on their lower ends as shown in Figure 9. The force needed to overcome friction between the dry lubricated surfaces of the latch and the shuttle rod was estimated between 35 and 70 kg using a friction coefficient of 0.05 to 0.1. The acme nut and gear motor are capable of exceeding this force by more than an order of magnitude.

When rotated, the nut ascends the lead screw within an operating gap as the dielectric shaft slides on the crowned spline. At the full extent of its travel in the gap, the nut flattens a thin disk spring and bears firmly on a thrust bearing that is backed by the track assembly. The spring normally preloads the bearing and thrust-washer combination to prevent them and the release shaft from rattling during vibration. It is sized by the launch limit load environment with 11 kg of force when flat. It also is intended to help ram the shaft assembly downward and out of the way upon release of the latch. The gap ensures that the assembly has room to move downward as the radiused edge of the release shaft is powerfully cammed by the force of the opposing latch, via the shuttle rod. The dielectric drive shaft slides on the crowned splines at the motor shaft to accommodate its axial motion.

The clamped tip of the square release shaft cannot turn. When the acme nut seats firmly on the thrust bearing, the lead screw begins to retract. Once it is clear of the shuttle rod the latch adjacent to it swivels to the right to release the deployer, which pushes the shaft assembly to the right as shown in Figure 9. This lateral motion is accommodated by the oblong retainer and a slotted penetration in the track assembly while the shaft rocks about 2 degrees on the crowned spline.

The shuttle rod or the release shaft will obviously yield or fail in some manner as contact stresses approach infinity at the bitter end of engagement. It was decided that such yielding could be made acceptable. The release shaft was therefore made of Nitronic 60™, which has an extremely high galling threshold of about 50 ksi, versus 2 or 3 ksi for other stainless alloys. Its strength and hardness are half or less that of the Custom 455™ shuttle rod. The shuttle rod should thus cut a clean groove in the edge of the release shaft tip during release.

The shaft tips have four sides and can be rotated to present fresh material. Nonetheless, it was hoped that once formed the grooves would have a better geometry for the intended purpose and that they would be work-hardened. If this were to be the case, the grooves could be re-used. The initial jettison test would simply be the final step in machining and subsequent operation would not produce a "failure."

The Latch Anomaly

The first jettison tests verified that the latch functioned, but the tip of the release shaft was grooved well into its center, as shown on the left in inset A, Figure 9. The deep curved groove traced the path of shuttle rod. This was not immediately understood. Subsequent tests on the fresh surfaces produced the same results. Then a faint peak of motor current with indiscernible duration was noticed on the strip chart. The peak was nearly coincident with a sharp reduction of current that immediately follows release. The release shaft was obviously jammed into contact with the accelerating shuttle rod and instantaneously stalling the motor as the kickoff springs did their job.

On a hunch, the thin disc spring that preloads the thrust bearing and the shaft assembly was removed, see Figure 9. This time a clean groove was produced that was on the edge of the release shaft tip only, as originally expected. The anomaly was caused by the fact that the force exerted by the thin disc spring exceeds the static friction force between the release shaft, latch and shuttle rod. The acme nut never climbed the lead screw into the gap to compress the spring. When the shuttle rod cammed across the radius on the tip of the shaft, the shaft had nowhere to go since it was still in contact with the flanged retainer below. The effective coefficient of sliding friction displayed by the surfaces lubricated with Vitrolube™ is estimated to be in the vicinity of 0.01, which is far below the anticipated value.

The fix for the problem was to use a very light spring for the operating gap in the release shaft assembly, its purpose being only to prevent the thrust bearing and washer from rattling in vibration. While working with the engineering model it became clear that the consequences of a release shaft shifting position during vibration are insignificant.

The latches were tested further by repeatedly releasing the latch over the same groove in the release shaft tip. It was confirmed that their geometry remains essentially unchanged after the first cycle of release.

CONCLUSIONS

The WISP DASS configuration evolved from the synthesis of electrical, radio frequency and mechanical design requirements with emphasis on Shuttle safety-critical functions. The requirements to safe the elements, provide high surface conductivity, low shunt capacitance, and electrically isolate the radiating elements were the most influential.

The combination of antenna element length, basic straightness and positional repeatability required by the plasma investigations is unprecedented for a STEM or BI-STEM. A straightness of ± 2 cm (± 0.8 inch) RMS, including hysteresis from multiple deployments, was achieved over the 23.6-m (930-in) length of each monopole by refining the forming process used at Astro Aerospace Corporation. This allowed a very comfortable margin to the overall straightness requirement.

The generous weight allocated to the DASS allows for a very robust design with minimal analysis. Consequently, a very fast detail design and fabrication process took place during months 7 through 11 of the program to produce an engineering model that is very close to the flight design.

The latch anomaly that was described was not serious, yet it reminds us that friction is not a very reliable phenomenon on which to base our designs. The tendency is to be conservative about the value of whatever coefficient we use, but this does not necessarily ensure success. The results also verified that controlled and well understood material yielding is acceptable for single event designs.

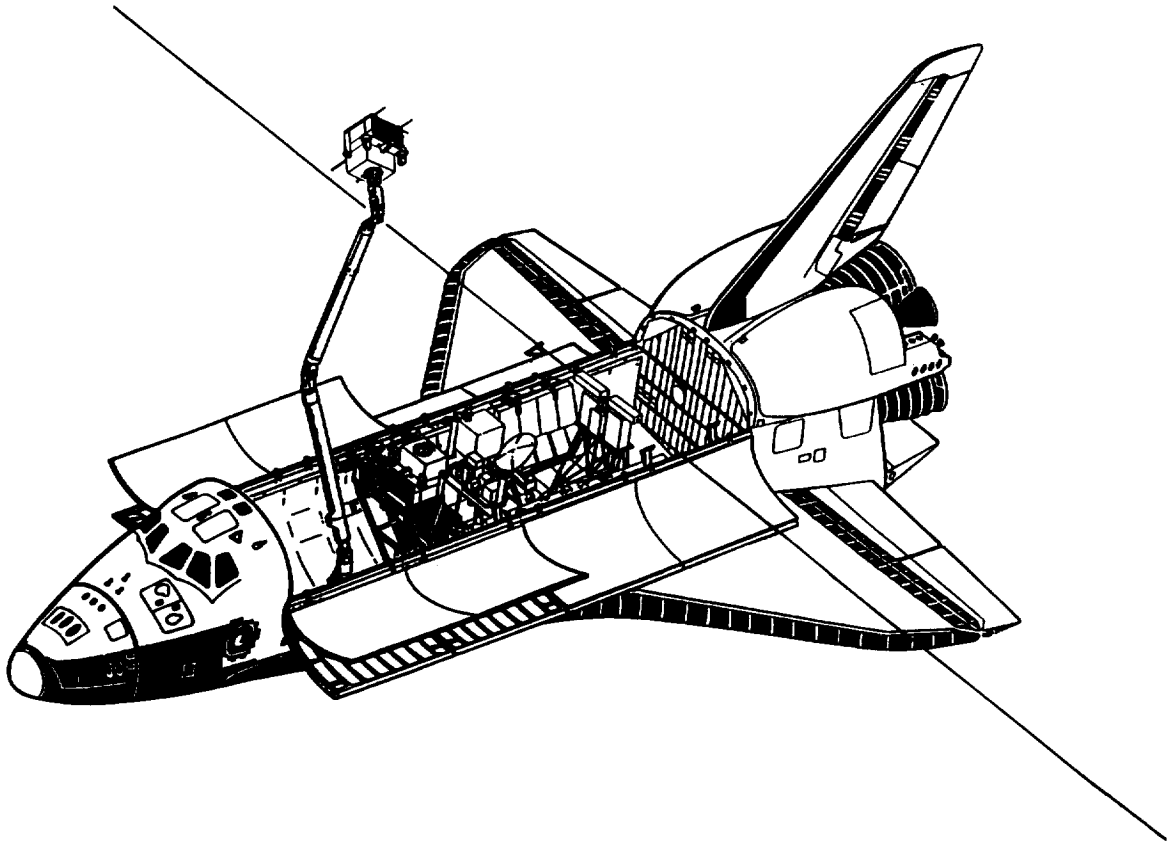


Figure 1. DASS Deployed on the Space Shuttle Orbiter.

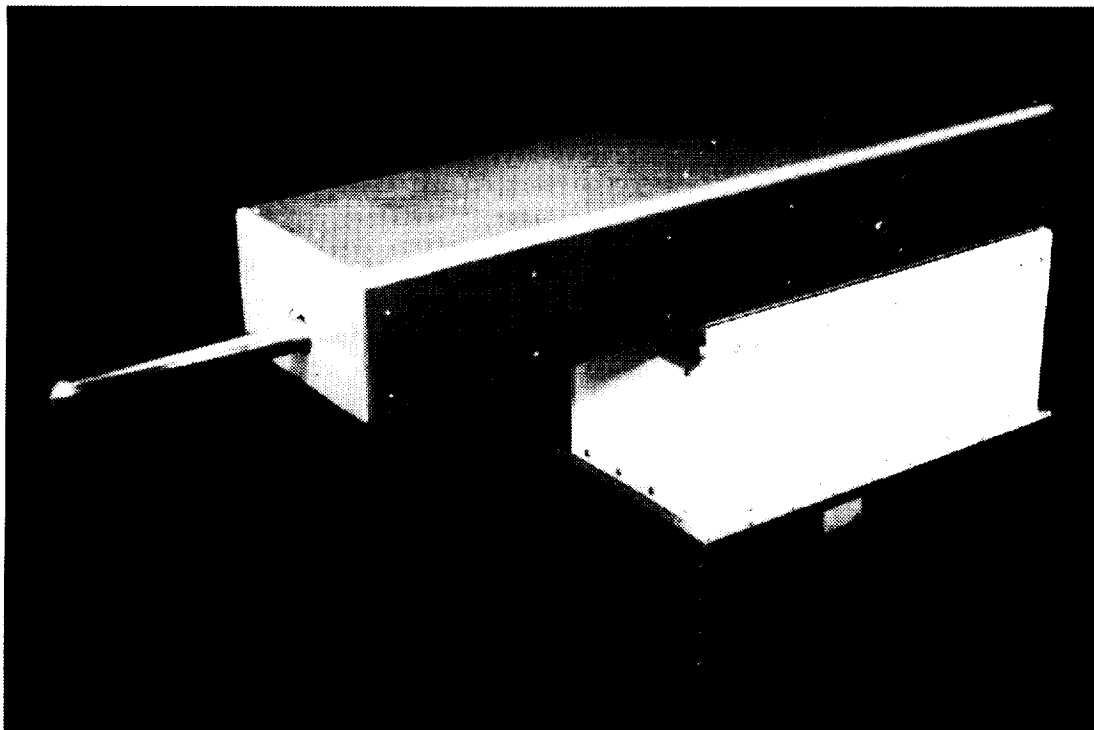


Figure 2. Antenna Element Assembly Partially Deployed.

5072

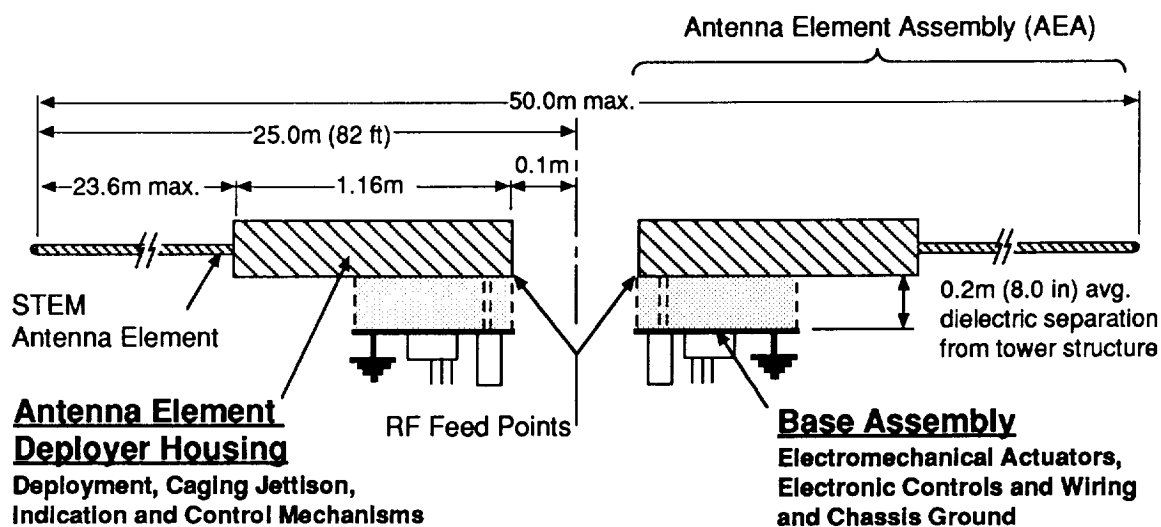


Figure 3. DASS Design Concept.

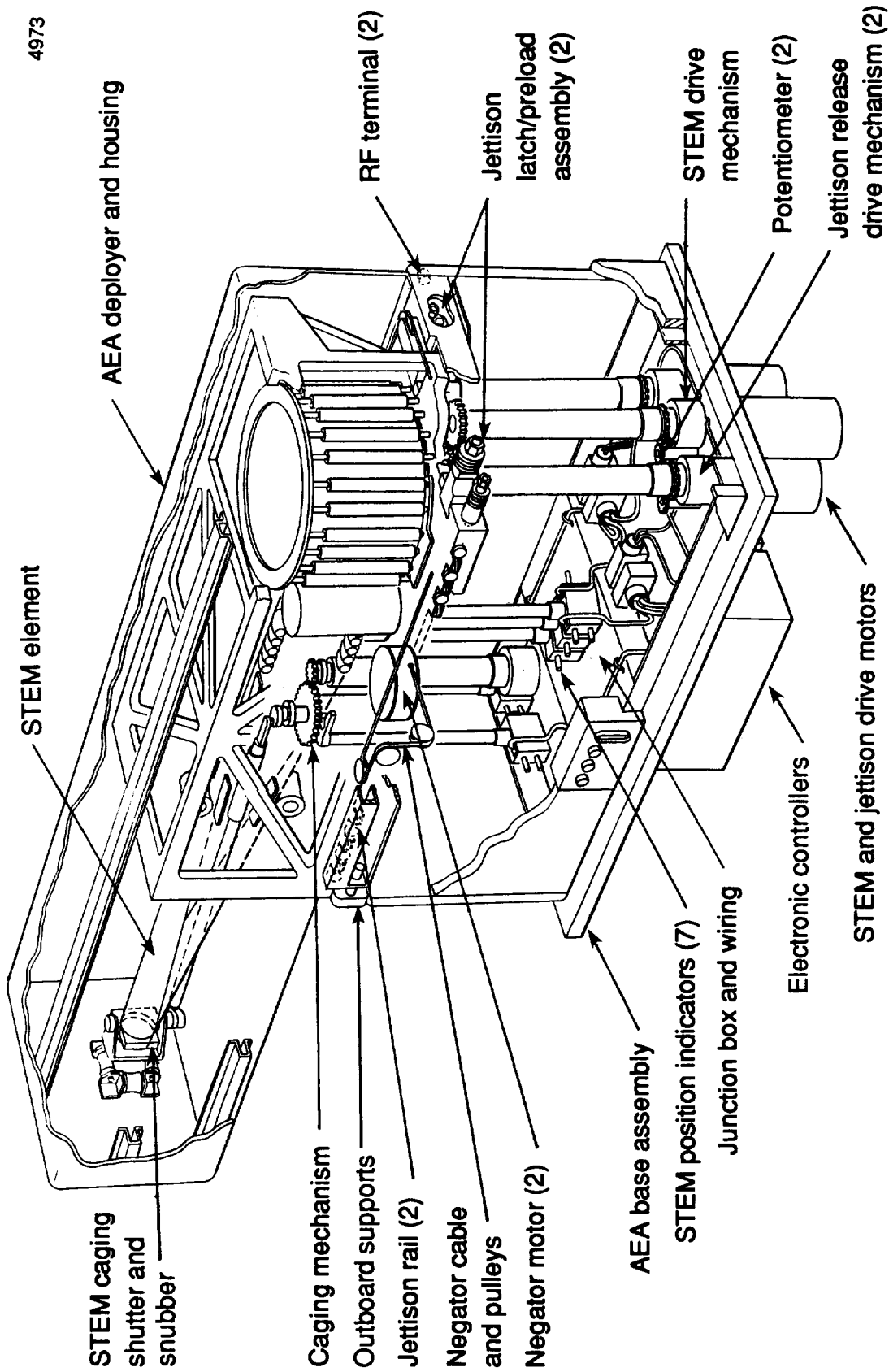


Figure 4. Cutaway View of the AEA.

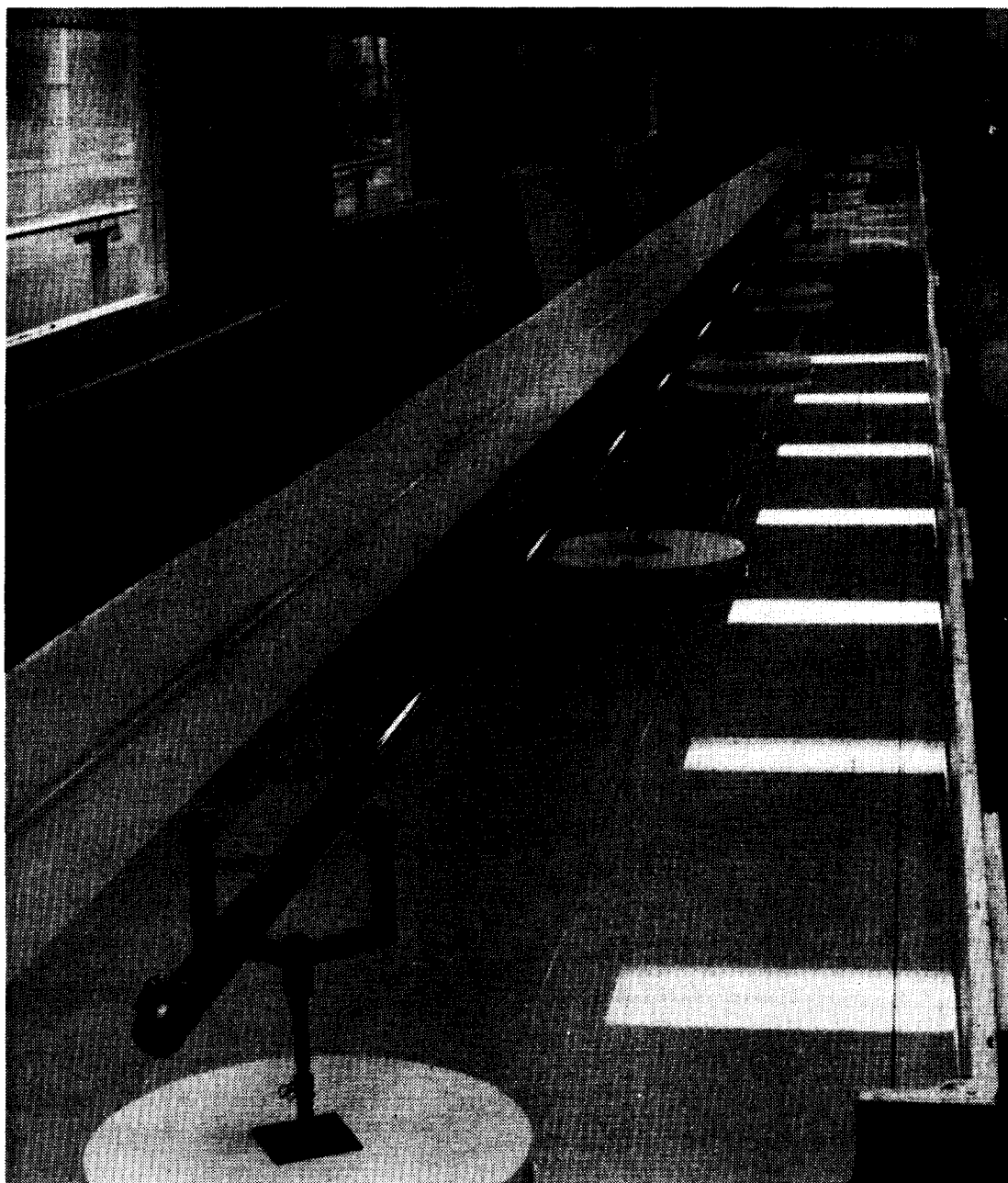


Figure 5. Deployed Engineering Model Antenna Element.

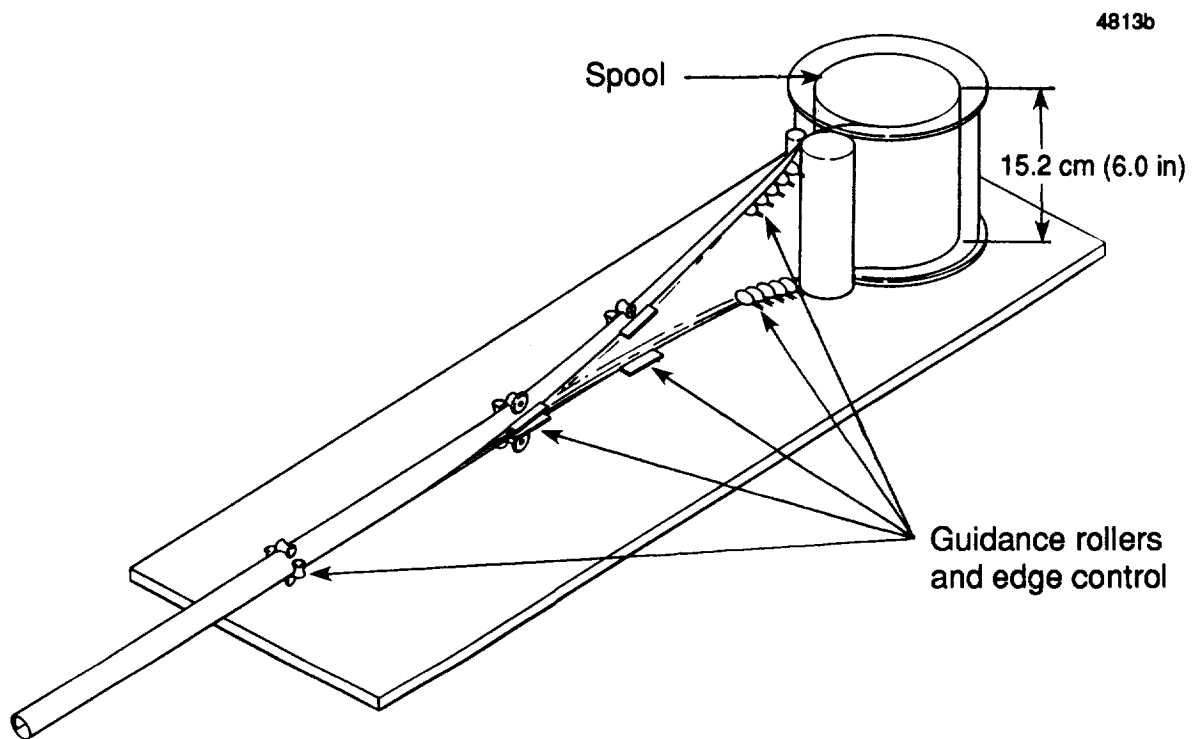


Figure 6. The STEM Mechanism.

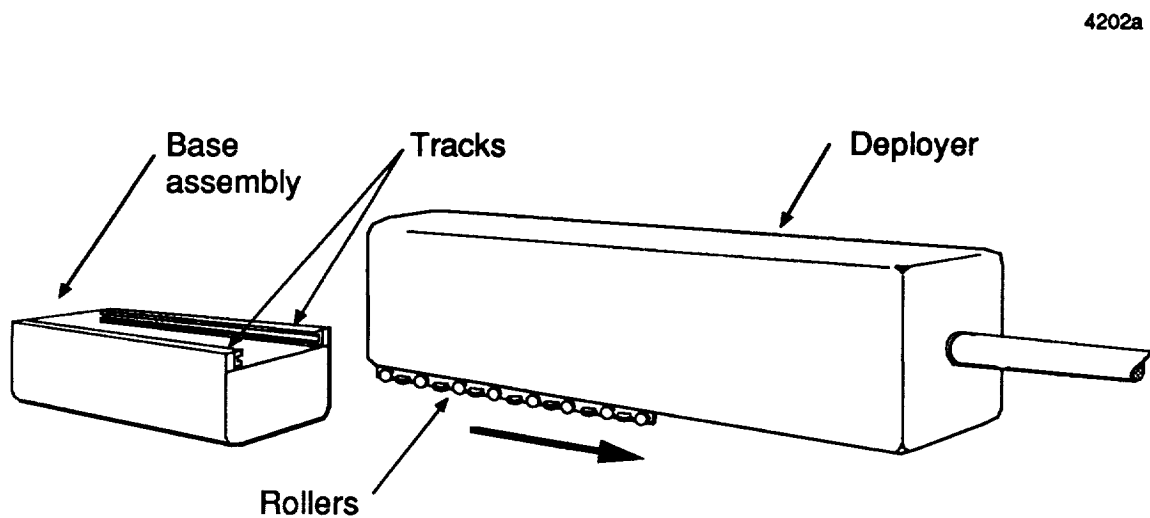


Figure 7. Deployer Mechanism Jettison Scheme.

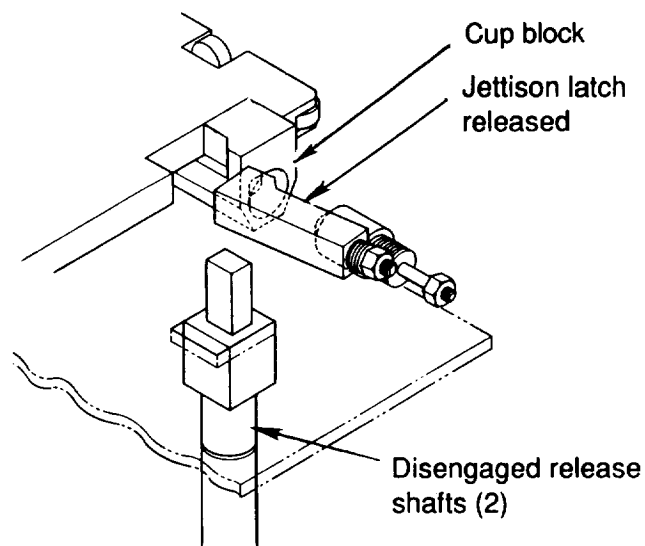
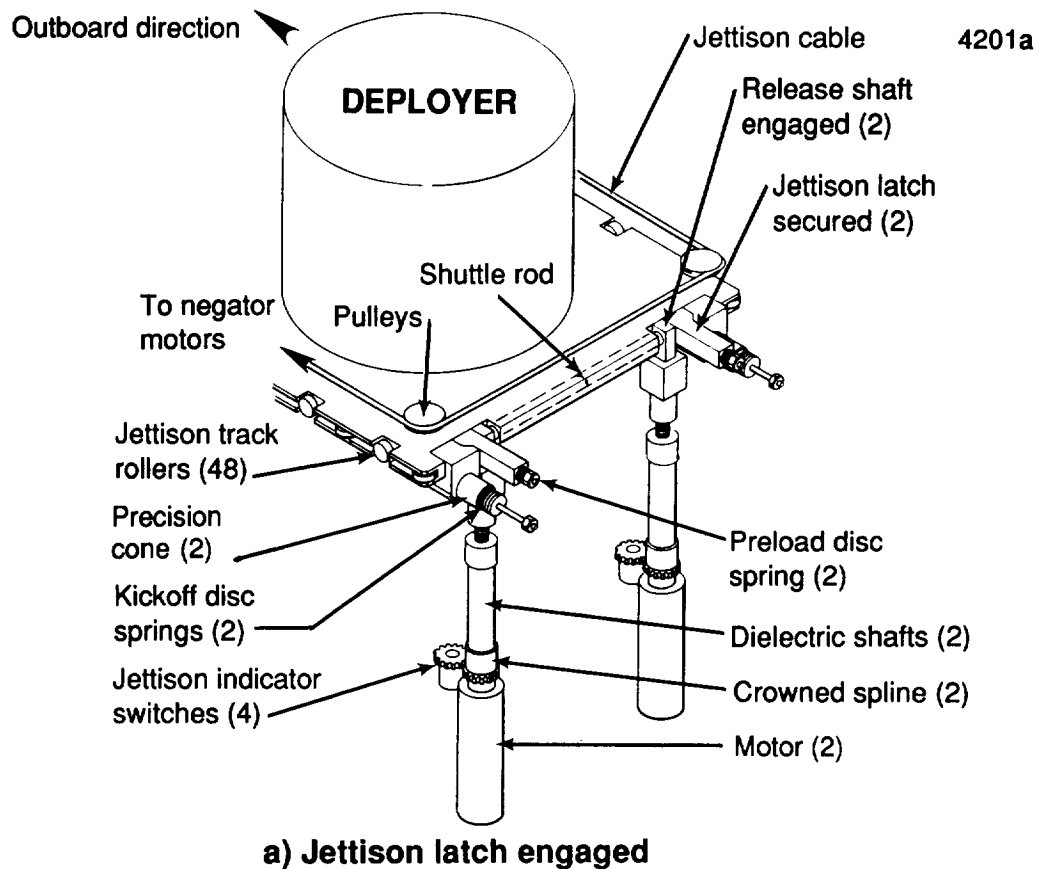


Figure 8. Jettison Latch.

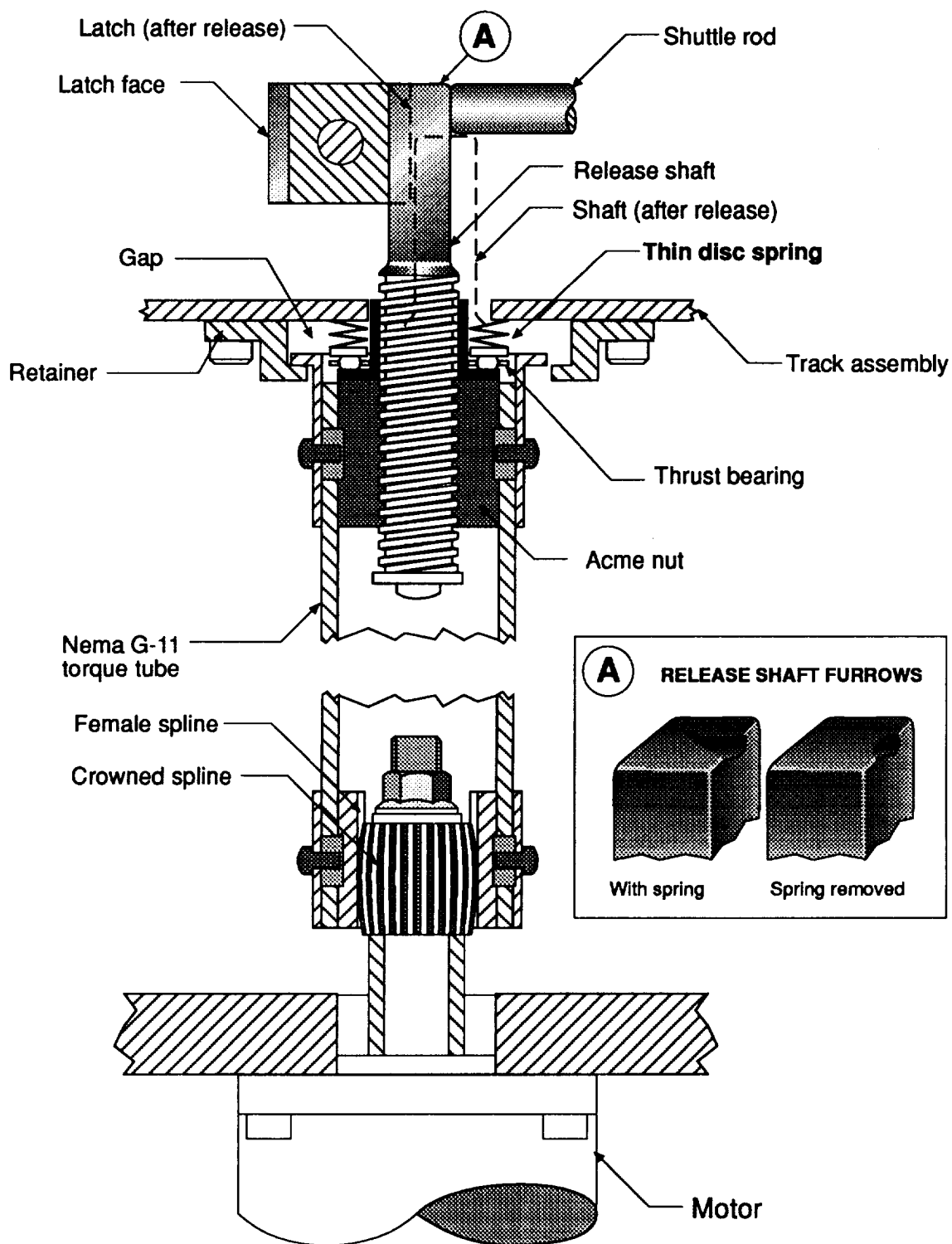


Figure 9. Jettison Latch Release Shaft Assembly.